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Mission-Related Design Requirements for the LEM Reaction Control Subsystem

Apollo Mission Planning Task Force

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Mission-Related Design Requirements for the LEM Reaction Control Subsystem [U]

Apollo Mission Planning Task Force [U]

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Report No. LED-540-24

26 Oct. 1964

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1. SUMMARY

The purpose of this report is to determine the mission-related functional requirements for the LEM Reaction Control Subsystem (RCS) and, further, to evaluate the capabilities of the present subsystem design in order to perform these functional requirements in both nominal and contingency situations. The critical parameters associated with these functions are identified and three specific parameters are selected for evaluation. These are: thruster burn time, propellant loading, and propellant distribution. The other parameters of the RCS, such as thrust value, minimum impulse, maneuver rate limits, Isp, and thruster configuration, are accepted at their present design values.

A worst nominal mission is developed and analyzed on the basis of simulation data and compared to the RCS propellant budget. A worst contingency mission is then developed (based upon the AMPTF Contingency Analysis) for the critical case of total RCS propellant and another mission is developed for the critical case for propellant loading in each of the redundant RCS tankage systems. Total propellant, of course, must provide for both cases, that is, either the maximum total requirement or twice the maximum single RCS tankage requirement, whichever is greater.

The worst single failure contingency requirements are developed and examined both on the basis of simulation data and on ΔV budget allocations. The loading of the ascent propulsion system becomes involved in the RCS evaluation since propellant from the ascent tanks can be cross-fed to the RCS thrusters. Further, the RCS in the nominal case provides a portion of the ascent ΔV which may be lost in the event of certain RCS failures. The contingency missions were also developed for case of no CSM rescue as well as for CSM rescue.

It is concluded that the present burn time specifications, propellant loading and distribution are adequate for the worst nominal conditions. It is further concluded that the present system design is adequate for all single failure situations if CSM rescue is provided. The latter conclusion is valid, however, only if (1) ascent engine propellant is used to feed the RCS thrusters during an ascent when 1/2 of the RCS propellant is unavailable due to a failure, (2) the ascent burn to 50,000 ft is completed on the low-thrust RCS jets for the case above or when due to an RCS thruster failure the ascent ΔV contribution of the RCS is

lost, and (3) an abort from powered descent can be made with the descent engine operated below maximum thrust.

The present RCS propellant loading provides (based upon satisfying the ΔV Budget requirements) a single RCS tankage margin of 26.8 lbs. of propellant for the worst single failure case with CSM rescue.

No changes to the RCS design are recommended at this time.

The RCS configuration as of June 1964 is described in Section 2. The ground rules, assumptions, functional requirements and critical parameters are discussed in Sections 3, 4.1 and 4.2.1. The approach to the problem is discussed in Section 4.2.2 and the worst nominal mission is developed in Section 4.2.4. A discussion of the RCS critical design mission is given in Section 4.2.5, and conclusions and recommendations are given in Section 5.

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2. LEM REACTION CONTROL SUBSYSTEMS DESCRIPTION

The Reaction Control Subsystem (RCS) provides the impulses that control the LEM in six degrees of freedom during all of the LEM inflight phases. The RCS consists of two independent, but interconnectable, bi-propellant sections; two helium pressurization sections, and sixteen 100-pound-thrust chambers that are arranged in clusters of four around the periphery of the LEM ascent stage (see Figs. 1 and 2).

The RCS may be operated in either a pulsed or steady state mode on command from the Stabilization and Control System (SCS) and the pilot's controller. In the fully automatic, semi-automatic and manual modes, control commands are processed in the SCS by a pulse modulator and jet logic networks, which establish when and which of the sixteen thrust chambers are to be fired. Both attitude control and translational control are provided by appropriate signal routing in the logic section of the stabilization and control system. Steady state operation of the thruster may be commanded from the pilot's control stick via a hardwire connection to emergency solenoids in the RCS thruster assembly. This operation by-passes the SCS logic.

2.1 HELIUM PRESSURIZATION SECTION

Propellant (fuel and oxidizer) tanks are pressurized by regulated helium gas acting upon the propellant tank bladders. Gaseous helium is stored in two spherical titanium tanks at 3,000 psi and 70^{o}F. Two redundant, explosively operated squib valves seal each helium tank until just prior to LEM separation from the CSM. A filter downstream of the squib valves traps possible debris and helium contaminants.

From the filter, each helium pressurization section splits into redundant lines. One line begins with a normally open, solenoid-operated, latch-type shut-off valve while the other line begins with a normally closed shutoff valve. Only one helium line is open at a time and should this fail the redundant line is opened. A two-stage, line sensing pressure regulator follows each shutoff valve. Each regulator is capable of reducing the helium pressure to propellant operating pressure; however, only one regulator in the line functions while the second remains passive. The single open helium line then splits into an oxidizer tank line and a fuel tank line. Quad check valves, one on each propellant tank line, prevent

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backflow and ensure isolation of the pressurizing helium and of one propellant tank from the other.

A relief valve, close to each helium port on the propellant tanks, is set to relieve at 250 psi.

2.2 PROPELLANT SECTIONS

Each of the two propellant sections contains two tanks, located in the LEM ascent stage. Each propellant tank contains a 3-ply Teflon bladder supported by a standpipe running lengthwise in the tank. The oxidizer tanks are loaded with nitrogen tetroxide (N_2O_4) and the fuel tanks are loaded with a 50-50 mixture of hydrazine (N_2H_4) and unsymmetrical dimethylhydrazine (UDMH). Although the tanks are sized for 614.4 lbs. of propellant (203.7 lbs. N_2O_4 and 103.5 lbs. 50-50 per system), they are presently loaded to 549.6 lbs. total, or 274.8 lbs. per system. Radiation-type quantity gauging devices, using sensors external to the propellant tanks, enable the quantity of propellant to be measured.

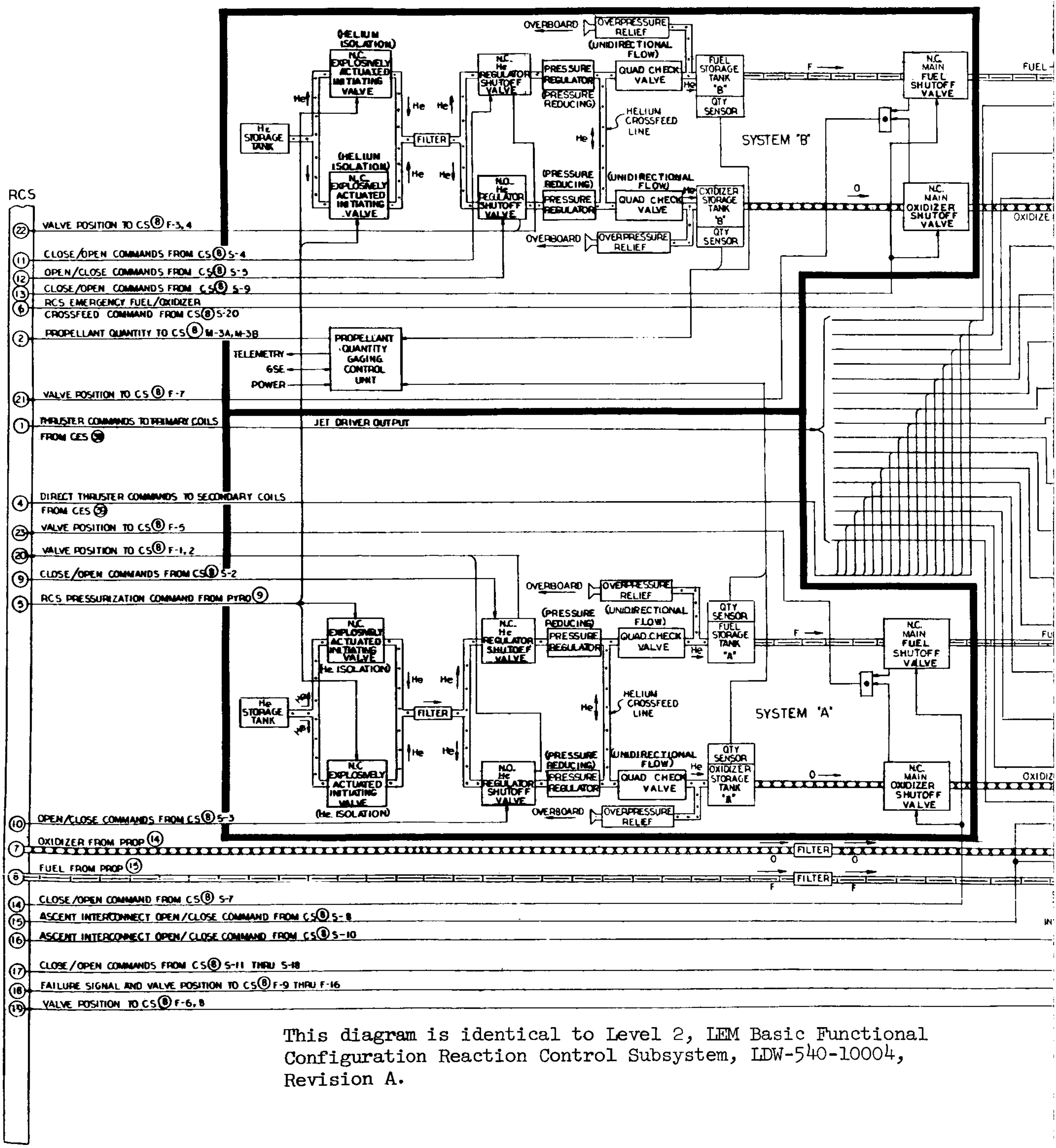
Latch-type, solenoid-operated shutoff valves permit isolation of any pair of four propellant tanks. From this valve, the propellant flows into a manifold feeding the eight thrusters. The manifolds from the two independent propellant sections can be connected through the actuation of normally closed solenoid valves.

Capability of feeding the RCS thrusters from the ascent propellant tanks is provided by four normally closed, solenoid-operated, latch-type shutoff valves.

An isolation valve stops fuel or oxidizer supply to a pair of adjacent thrusters. There are sixteen of these, each manually operated from a switch on the control panel.

2.3 THRUST CHAMBER ASSEMBLY

The thrust chamber assemblies section consists of sixteen thrusters grouped in clusters of four. Each thruster is capable of operating in a pulse or steady state mode. The propellant lines, valves and injectors are encased in a radiation shield and insulation blanket that provides protection from solar radiation and radiation from the operating engine while at the same time radiating thrust-chamber-generated heat into space. This insulation also prevents heat loss during cold soak. There are two injector valves for each thruster. One introduces oxidizer to the thrust chamber while the second introduces fuel. They are double coiled, electrically operated valves which receive their command signals from the control electronics section.



This diagram is identical to Level 2, LEM Basic Functional Configuration Reaction Control Subsystem, LDW-540-10004, Revision A.

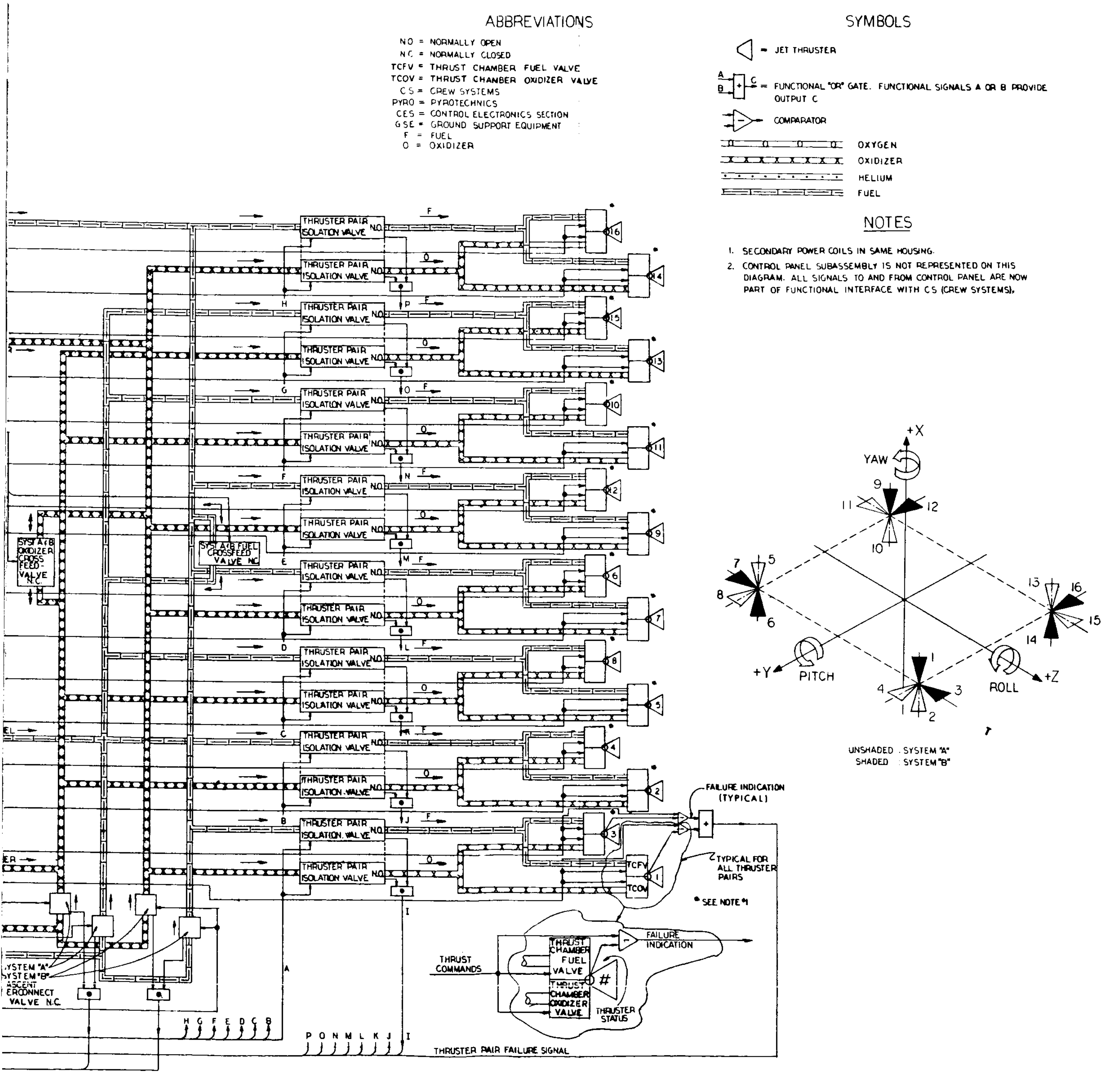


Fig. 1 LEM Reaction Control Subsystem Functional Diagram

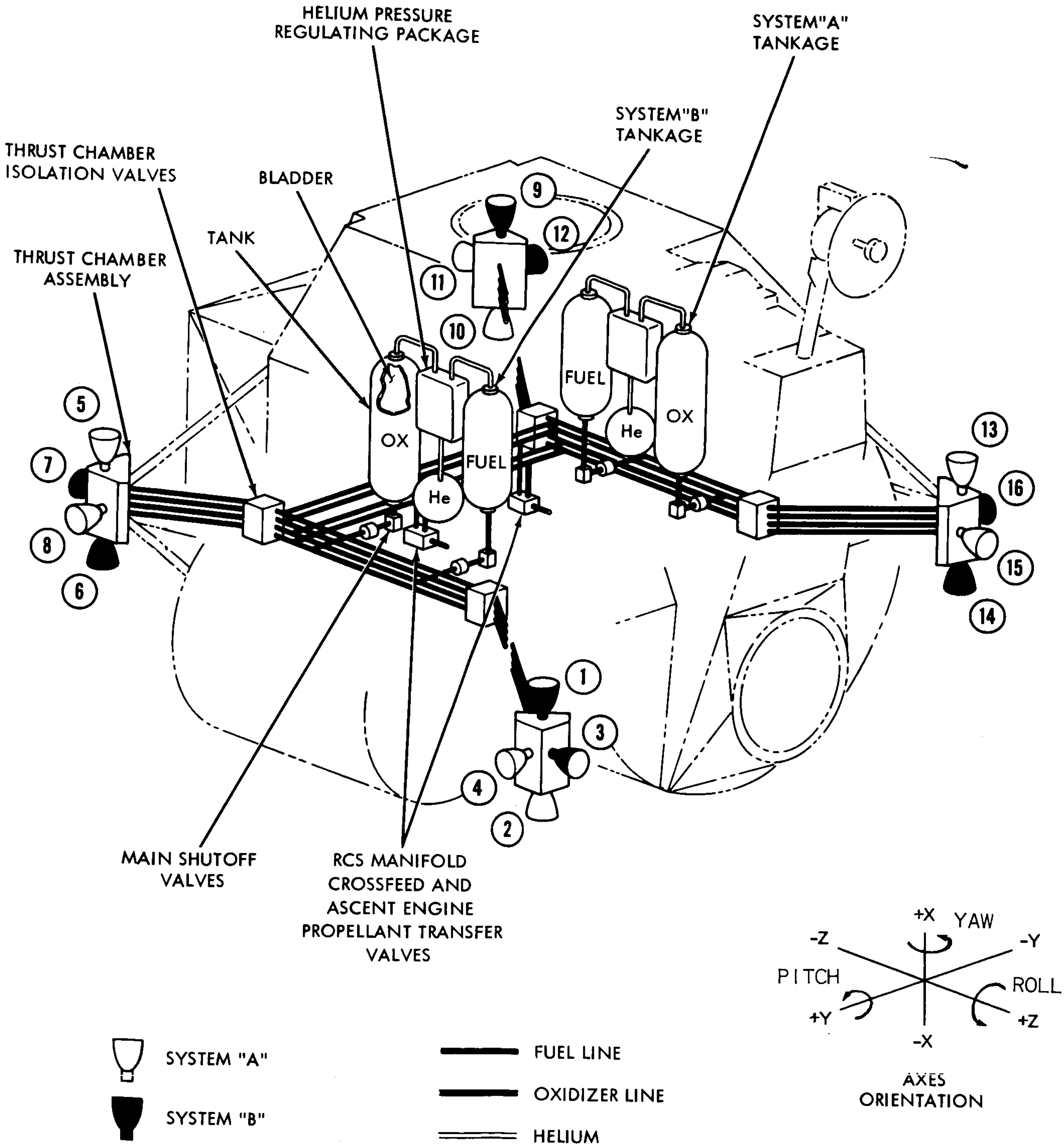


Fig. 2 Reaction Control Subsystem Installation

3.0 MISSION RELATED DESIGN CRITERIA

3.1 APPLICABLE SPACECRAFT DESIGN GROUND RULES

Most of the following are ground rules established by the AMPTF Phase I Progress Report (Ref. 1). Ground rules relate the RCS to the total mission requirements and serve to clarify any existent bounds.

1. Both the command and service modules (CSM) and LEM shall be capable of performing the rendezvous and docking maneuvers required, assuming the LEM orbit has a clear pericynthion. The passive vehicle shall have a transponder and be stabilized.

2. Docking maneuvers are to be controlled manually.

3. Inflight contingency actions will be initiated primarily by manual means unless emergency condition requirements are such that manual operation is inconsistent with crew safety.

4. The spacecraft shall be designed so that any one crewman can perform all functions required to accomplish a safe return to earth from any point in the mission, assuming no further contingencies.

5. Whenever possible, a system shall be designed so that the failure of any single element shall not cause the loss of a crew member.

6. Visual LOS from LEM to the landing site is required during the LEM descent phase, beginning at 7-10 mi. slant range from the site.

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4.0 LEM RCS CRITICAL DESIGN REQUIREMENTS

4.1 FUNCTIONAL REQUIREMENTS

The Reaction Control Subsystem (RCS) of the LEM is required to perform the following functions during the entire active LEM mission.

4.1.1 Attitude Control

LEM's body axes must be oriented within a specified angular range about a fixed attitude. Coarse and fine limit cycle operations must be available about each axis of rotation. Such control consists of monitoring the vehicle's angular drift and, whenever the limit cycle deadband is reached, minimum impulses of the RCS thrusters are used to reverse the drift.

The use of a coarse limit cycle is satisfactory throughout all coasting phases, whereas a fine limit cycle is required during main engine firings. These functions must be provided by the RCS except during powered descent where the gimballed descent engine maintains pitch and roll control. However, the RCS maintains yaw control in the fine limit cycle during powered descent.

The RCS must maintain attitude control in a fine limit cycle in all axes during powered ascent because the ascent engine is not gimballed.

4.1.2 Compensation for Moment Unbalance

During the powered ascent of the active LEM mission, moment unbalances will exist. These are due to: 1) c. g. offset due to mass properties, (2) thrust misalignment, (3) pressure drop mismatch in fuel and oxidizer lines, (4) pressure mismatch in fuel and oxidizer tanks, (5) initial fuel and oxidizer unbalance at liftoff. The RCS must provide continuous compensation during powered ascent. This moment control must be accomplished to the accuracy of the fine limit cycle.

During powered descent, similar moment unbalances will exist; however, the gimballed descent engine provides the required compensation during this phase.

[redacted]

4.1.3 Rotations

The RCS must provide the necessary torques to rotate the LEM vehicle about its X , Y and Z axes. This is necessary during all phases of the LEM mission. Most of the required rotations will take place in the X-Z plane, i. e. , pitch maneuvers. That is, the LEM is normally stabilized so that the X-Z plane is in the orbital plane. During the unpowered phases, rotations are necessary to orient the LEM vehicle in order to take star sightings which are required for fine alignments of the IMU. Pitch rotations are required to aim the landing and rendezvous radars at the CSM during the separation and coasting descent phases of the mission. Pitch maneuvers are also required to allow crew visibility of the landing sight during descent and of the CSM during rendezvous. Pitch maneuvers are required for proper orientation of the LEM prior to commanded insertion into a Hohmann descent. Similar orientations, provided by the RCS, are required prior to powered descent, hover to touch-down, powered ascent, the rendezvous and docking phases. During powered phases, yaw rotations and programmed pitch maneuvers must be performed by the RCS.

4.1.4 Ullage Maneuvers

Ullage maneuvers are required prior to each main engine thrusting in order to precipitate the propellant to the bottom of the tanks. In order to accomplish this, a small ΔV contribution from the RCS of 3 to 5 fps will be required using paired X axis thrusters.

4.1.5 Translations

All translation maneuvers required by the LEM other than ascent and descent will be small ΔV changes in the total velocity vector. Such ΔV's must be provided for by the RCS where it is deemed not feasible or possible by a main engine firing. At separation, the LEM must acquire a small ΔV in order to establish a safe distance between it and the CSM before insertion. (The descent engine is used for insertion.) Horizontal translations, during hover, may be required for final selection and steering to the touchdown point. This is necessary at low altitudes when vehicle tilt for translation is not desirable. During the ascent phase, midcourse corrections must be provided after burnout of the main engine. At rendezvous, the total velocity vector of LEM must be made to match that of the CSM. This allows final alignment before the docking maneuver is performed. The docking maneuver will be a slight increase in ΔV to allow the docking hatch to be secured.

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4.1.6 RCS Use In LEM Propulsion Backup of Service Module Propulsion System

The LEM propulsion systems can be used as a backup to the service module propulsion systems as discussed in Ref. 11. This backup would be provided for aborts from trans-lunar coast and lunar orbit. Static stability considerations do not permit the ascent engine to be used and thus ascent propellant is available only by burning it through the RCS thrusters. If LEM propulsion backup is limited to CSM failures occurring before LEM powered descent, there is no requirement for LEM RCS use for a long burn transearth injection, since the descent engine alone is sufficient. However, the RCS may be called upon to provide midcourse corrections during transearth coast. Corrections of up to 300 fps may be required.

4.2 DISCUSSION

4.2.1 Critical Parameters

In this analysis, thruster level, thruster minimum impulse, I_{sp}, SCS system deadbands, and angular rate limits have been accepted at the current nominal design values as listed below.

- Thruster level = 100 lbs.
- Minimum impulse 0.6 lb sec.
- I_{sp} values: (Ref. 2)

  I_{sp} = 295 sec. for continuous thruster operation

  I_{sp} = 270 sec. for each maneuver

  I_{sp} = 230 sec. for ascent stage c.g. compensation about pitch and roll axes

  I_{sp} = 100 sec. attitude control pulsed operation
- SCS deadbands: narrow $\pm 0.3^{\circ}$ wide $\pm 5.0^{\circ}$
- Angular rate limits. During powered phases when the LEM is controlled in a completely automatic mode, maximum rates of 10°/sec. in pitch and 5°/sec. in yaw and roll are provided. In the manual mode, the SCS rate gyro limit is 20°/sec. in all three axes.

[redacted]

In addition, the vehicle mass properties conform to the present control weight as outlined in Ref. 3. The critical parameters considered in this report are therefore limited to the following:

1. RCS thruster burn time. The worst burn time will result from the mission which consumes the maximum amount of propellant through the RCS thrusters as explained in section 4.2.5.3.

2. Propellant quantity. The total propellant available in systems "A" and "B" and RCS allotment available in the ascent propulsion system is of prime concern in planning the nominal mission and any contingencies.

3. Propellant distribution. The distribution of the propellant must accommodate all contingency requirements on the RCS such that at any point along the nominal mission, should it be necessary to abort, the RCS will be able to perform all functions to enable the astronauts to return to the CSM safely.

4.2.2 Critical Mission Selection

The critical design mission was arrived at by examining the worst nominal mission and the capability of LEM to complete an abort mission, without CSM rescue, in a single failure condition. This failure may be either within the RCS or in one of the related subsystems aboard LEM. The aborted mission must be computed to completion (complete docking) in order to determine the capability of LEM to complete the abort with the present RCS design.

The worst nominal mission is computed to see if, on the basis of simulated data, the present propellant budget is adequate. However, the critical design mission will be determined by failures which affect the RCS propellant consumption rate or propellant loading.

Analysis has shown that aborts anywhere prior to powered descent or after powered ascent cannot be critical to RCS propellant loading or consumption. Hover to touchdown can also be eliminated as a critical phase because for any failure during this phase the same failure can take place during lunar stay, which is a more critical phase. Although an abort from hover may require a one hour parking orbit (and thus an ullage maneuver), an abort from the lunar surface requires more propellant for rendezvous. Hence, the failure on the lunar surface will require more RCS propellant than the same failure during hover to touchdown.

The AMPTF contingency analysis (Ref. 12) was used to find failures which would affect either RCS propellant consumption or propellant loading. These failures were then postulated during each of the critical phases and the ability of LEM to complete the aborted mission was examined.

It is important to note that contingencies that impose both total and single RCS system propellant requirements must be considered. The total tank loading must be sufficient to insure that 1/2 of the total will satisfy the maximum single system requirement.

4.2.3 References for Propellant Requirements

- Translation Requirements

  The LEM Minimum ΔV Budget is used for nominal ΔV requirements and for ΔV requirements for direct aborts from the lunar surface. However, data available from simulation and computer runs and from knowledge of the systems aboard LEM indicate that the ΔV allotted by the LEM Minimum ΔV Budget may be conservative. The ΔV budget is not applicable to all contingency situations and therefore in these cases simulation data must be used. Simulation results can be used for RCS propellant requirements during the hover to landing and docking phases. Analysis of the various possible trajectories yields rendezvous ΔV requirements for the nominal case as well as for aborts from descent and ascent. Furthermore, the percentage allotments in the LEM Minimum ΔV Budget for guidance errors and evaluation uncertainties are considered to be high. The LEM Minimum ΔV Budget calls for 122 fps for guidance errors and 61 fps for evaluation uncertainties in ascent. However, accurate evaluation of these errors and uncertainties has not been made. Studies conducted by the GAEC LEM Dynamics Group indicates that 25 fps for guidance errors and 15 fps for evaluation uncertainties may be adequate. The values become important because of the RCS contribution to the ascent and therefore help determine both the nominal and contingency requirements.

  Two approaches, then, will be used to evaluate RCS propellant requirements in the nominal and various contingency missions. As a result, there will be two missions which are critical to RCS design. One will result when the LEM Minimum ΔV Budget is used to dictate propellant requirements and a second critical design mission will result when simulation data is used. Both of these cases will be outlined in Section 4.2.4 of this report.

- Rotational Requirements

  In order to determine the propellant required for rotational maneuvers, maximum angular rates must be specified as well as the angular excursions involved. During the period of acceleration up to the maximum rate, an angular displacement will develop before the RCS thrusters shut off and the vehicle coasts (rotationally about its c.g.) at the specific maximum rate.

  Because most expected rotations will be about the Y axis, the I_{YY} moment of inertia was selected for all phases in order to obtain the information in Figure 4. The abscissa value shows the amount of propellant needed to establish a pitch rate. The same amount will be necessary to halt the rotation later. Also shown are the angular displacements achieved from initiation of the rotation until RCS thrusters are shut off upon reaching a selected rate. This angle is 1/2 of the total in a full maneuver with no coasting.

4.2.4 The Worst Nominal Mission

The worst nominal mission is defined as that particular nominal mission which imposes the greatest propellant requirements upon the RCS. This will determine whether or not the present design is capable of performing the range of no-failure missions. The worst nominal mission also provides a reference propellant schedule up to any abort point. This includes all possible nominal requirements which may diminish the propellant supply prior to an abort. Both simulated data and ΔV Budget worst nominals are considered.

4.2.4.1 Simulated Data Worst Nominal Mission

The worst nominal mission sequence of events may be described by referring to the chart shown in Figure 3. The left box in Figure 3 indicates a particular phase beginning with LEM checkout and alignment, prior to LEM/CSM separation, through lunar stay and ultimately LEM/CSM docking. For convenience, the descent portion of the mission is shown separately from the ascent portion. The RCS thrusters during each phase of the mission may be automatically or manually fired. The automatic mode of operation depends upon the information from the LGC, whereas, for example, the manual mode and semi-automatic mode may be used to obtain star sightings for IMU fine alignments. Figure 3 indicates manual or automatic modes of RCS firings for each phase of the nominal mission. The required operations during the mission phases are described below and values derived for this mission are presented in Table I.

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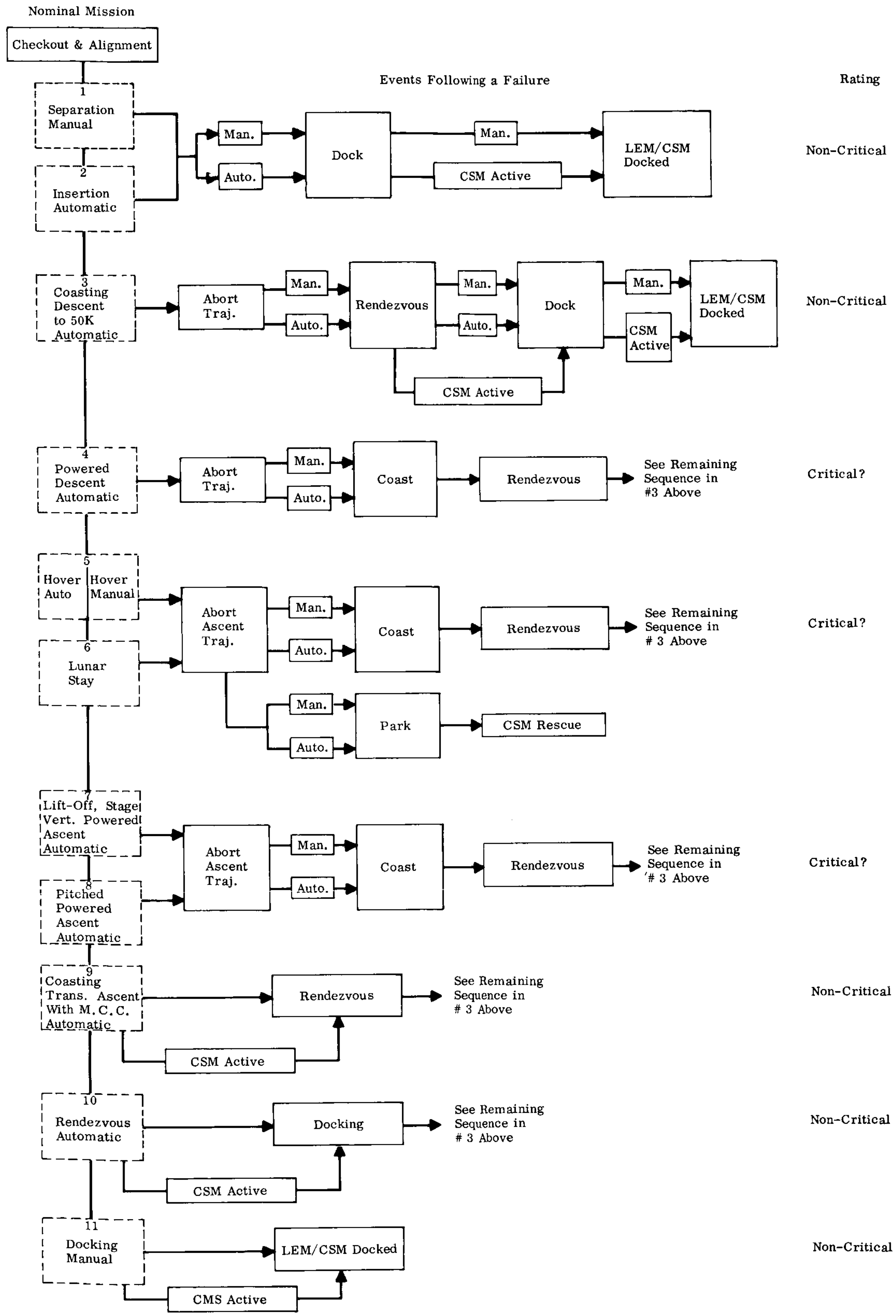

Fig. 3 LEM Nominal Mission and Abort Paths

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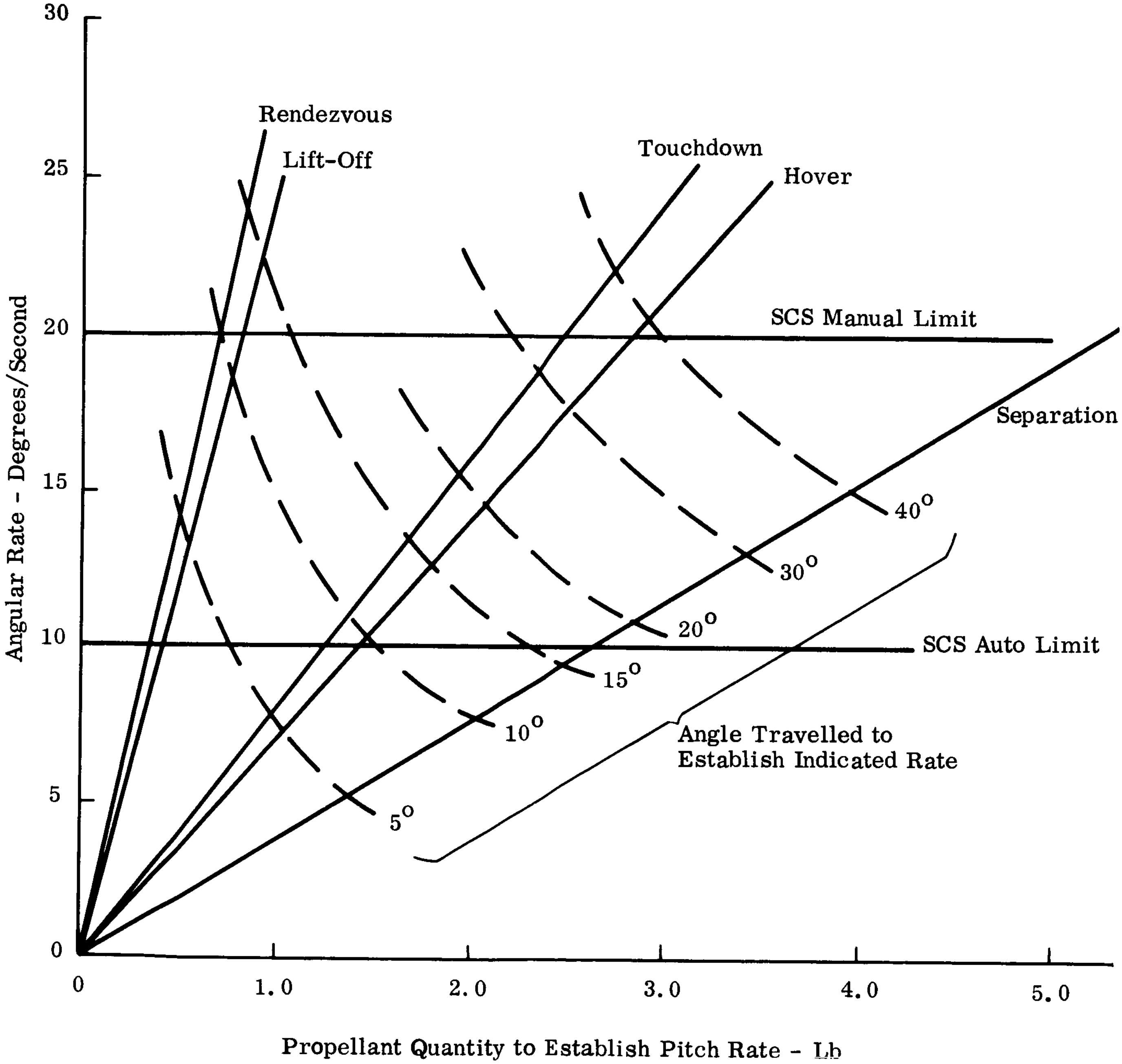

Figure 4 LEM RCS Fuel Consumption to Establish Angular Pitch Rates for Various Mission Phases

- Prior to LEM/CSM Separation

  During the checkout phase, prior to separation, each RCS thruster is fired separately, to check full thruster firing. Although, for the Design Reference Mission, the fine alignment of the LEM IMU was performed after separation, there is the possibility that this operation will be performed prior to separation using the LEM RCS thrusters. Since the latter is a more severe case for tank sizing considerations it was assumed herein.

- Separation

  The separation phase involves an RCS thruster firing for a translation ΔV of 5 fps. During this firing, LEM attitude is maintained within a 0.3° deadband. A pitch maneuver is performed in order to aim the landing radar at the CSM. The vehicle is stabilized within a 5° deadband during the non-thrust part of separation.

- Insertion

  Immediately prior to a commanded insertion into a Hohmann descent, the RCS thrusters are fired for: (1) a second IMU fine alignment, (2) a pitch maneuver to prepare for insertion, and (3) an ullage maneuver. During firing of the RCS thrusters, a 0.3° deadband is maintained. Insertion into a Hohmann coasting descent is performed by the descent engine.

- Coasting Descent

  After insertion, a pitch maneuver is required to allow tracking of the CSM with rendezvous radar for orbital determination. During coast, a 5° deadband is maintained for attitude control. A third fine alignment of the IMU is then performed. At 70,000 feet, a pitch maneuver is required to check the landing radar. An orientation maneuver of LEM is required prior to initiation of powered descent. An RCS ullage maneuver is performed for preparation of descent engine firing.

- Powered Descent

  During powered descent, a 0.3° deadband is maintained for attitude control. This is effected in pitch and roll by the gimballed descent engine while the RCS provides yaw control. For the critical mission the powered descent is assumed to begin with the +Z axis pointing at the lunar surface. Therefore, at approximately 25,000 feet, a 180° yaw maneuver is required to obtain landing radar altitude information. A 40° pitch maneuver for LOS is required at approximately 14,000 feet as is a final pitchover to hover orientation at approximately 200 to 1000 feet.

- Hover to Landing

  The hover to landing phase has been studied on simulators. Although data exist which outline various maneuvers performed while on manual control during this phase, it is difficult to present a worst case description of the events. However, data are readily available for RCS propellant consumption during the phase; therefore, only a propellant consumption and not the associated sequence of events is shown. In order to create a worst case, additional maneuvers were assumed to extend to the 3 min. hover limit and the associated propellant requirements are added to the simulation results.

- Lunar Stay

  During lunar stay, the RCS system remains passive except for checkout firing just prior to powered ascent.

- Powered Ascent

  After staging and ignition of the ascent engine, the RCS thrusters orient the vehicle for the 12 sec. vertical rise. During the vertical rise a yaw maneuver is performed to bring the X-Z plane of LEM into the ascent orbital plane. During powered ascent, the moment unbalance, resulting from c.g. offset, is compensated for by two +X axis thrusters firing in unbalanced couples. This maintains attitude with a 0.3° deadband and contributes a positive ΔV.

- Coasting Ascent

  At the end of the pitched powered ascent phase, a 0.3° deadband is required for insertion into the coasting transfer ascent. During coast, a 5° deadband is maintained for attitude control. It is assumed for the critical design mission that the RCS thrusters perform a pitch maneuver to allow crew visibility of the CSM. The attitude selected at the end of this maneuver is such as to allow communication with CSM and earth and radar tracking of the CSM throughout coast. Nominally, during the coasting transfer ascent, three midcourse corrections are performed by the RCS during which time a 0.3° deadband is used. In order to obtain a worst case, an ascent transfer orbit with a 210° central angle from insertion to intercept was used.

- Rendezvous

  At 5 nautical miles, the terminal rendezvous phase begins. During this phase, RCS firings for rendezvous maneuvers are performed. Deadbands of 0.3° and 5° are used during and between firings, respectively. Prior to docking, two pitch maneuvers are required for an X-axis alignment with the CSM.

- Docking

  The docking phase ΔV and propellant requirements were obtained from simulation test data. A total propellant consumption amount, but no breakdown of maneuvers, was available from these data.

4.2.4.2 The LEM Minimum ΔV Budget Worst Nominal

The RCS propellant requirements for the worst nominal mission, as dictated by the LEM Minimum ΔV Budget (Table II) and Reference 2, are outlined in Table III.

4.2.4.3 Summary of Worst Nominal Results

In the worst nominal mission the two key parameters are total propellant and burn time. Propellant distribution is not significant since both sets of RCS tanks are available. The worst nominal missions described above require a total of 321.77 lbs. of RCS propellant for the case based upon simulated data and 496.3 lbs. of RCS propellant in the ΔV Budget case. The present RCS tanks (using LEM control weights) are loaded to a total of 549.6 lbs. of useable propellant and therefore are adequate for all nominal missions.

Analysis of these mission events based upon Table I propellant consumption figures shows an accumulated burn time of 126.2 sec. pulsed and 123.0 sec. steady state on the most used thruster. This is within design specification value of 500 sec. pulsed and 500 sec. steady state.

[redacted]

TABLE I - WORST NOMINAL MISSION
SIMULATED DATA

Mission Events & Phases	No. of Lbs. Propellant
1. RCS checkout in lunar orbit	4.1
2. IMU fine alignment before separation (Ref. 6)	11.74
3. Separation	
a. Translate $\Delta V = 5$ fps	15.7
b. Pitch to aim landing radar at CSM	2.6
c. Limit cycle - attitude control - 0.3^{o} and 5^{o} deadbands	0.06
d. IMU fine alignment (Ref. 6)	6.24
e. Orientation (pitch) required for insertion	2.6
f. Ullage maneuver	6.8
	34.00
4. Insertion	
a. Limit cycle in yaw	.01
5. Coasting descent	
a. Pitch maneuver required to track CSM with rendezvous radar for orbital determination	2.6
b. Limit cycle - 5^{o} deadband	0.19
c. IMU fine alignment (Ref. 6)	6.24
d. Pitch maneuver at 70,000 ft. to check landing radar	2.6
e. Orientation for initiation of powered descent at 50,000 ft.	2.6
f. RCS ullage maneuver	6.7
	20.93
6. Powered descent	
a. Limit cycle - 0.3^{o} deadband	0.18
b. 180^{o} yaw maneuver at 25,000 ft. required to allow landing radar information to be obtained	2.0
c. Pitchover to hover orientation	1.4
d. 40^{o} pitch for LOS at 14,000 ft.	1.75
	5.33

[redacted]

TABLE I - WORST NOMINAL MISSION (continued)

Mission Events & Phases		No. of Lbs. Propellant
7. Hover to landing		
a. Simulation worst case (Ref. 9)		30.8
b. Four (4) pitchovers & two (2) yaws, extension of simulation data to cover 3 min. hover.		7.76
		38.56
8. Lunar stay		
a. RCS checkout		4.1
	Total Descent	118.77
9. Powered ascent		
a. RCS attitude control and C.G. compensation		85.0
b. Yaw maneuver required for preparation of pitched powered ascent		0.81
c. Pitchover for pitch profile		0.76
d. Orientation to put thrust vector vertical		0.80
		87.37
10. Coasting transfer ascent		
a. Limit cycle - 5^{o} deadband		2.6
b. Pitch maneuver to allow crew visibility of CSM		0.35
c. Three (3) midcourse corrections		
C-1 limit cycle - 0.3^{o} deadband		0.22
C-2 ΔV (25 fps)		14.6
		17.77
11. Rendezvous		
a. Translations		83.4
b. Two (2) pitch maneuvers to align along X-axis for docking		0.33
c. Limit cycle - 0.3^{o} deadband		1.32
d. Limit cycle - 5^{o} deadband between 1st and 2nd burns and between 2nd and 3rd burns		0.17
		85.22
12. Docking		
a. Simulation (Ref. 8)		12.65
	Total Ascent	203.01
	Total for Mission	321.78

[redacted]

TABLE IIa

LEM MINIMUM ΔV BUDGET (FT/SEC)

DESCENT STAGE

(SEPARATION WT = 29,870 lbs.)

MISSION PHASE \ BUDGET ITEM	OPEN LOOP		GUIDANCE	FLIGHT MECHANICS CONTIN-GENCIES	EVAL. UNCER.	TOTAL
	ABSOLUTE MINIMUM	FLEX. ALLOW.				
LEM SEPARATION (RCS)	5					5
DESCENT TRANSFER ORBIT INSERTION	97		2		1	100
DESCENT TO SURFACE						
o Initial Deboost	5785	165*	120		60	6130
o Landing Approach Translation and Touchdown		900			250	1150
					Total ΔV	7385

* Shaped for pilot visibility

MISSION PARAMETERS

1. CSM in 80 n. mi. altitude circular parking orbit
2. LEM powered descent initiated at 50,000 ft.
3. $(T/W)_o$ at pericynthion = 0.356

TABLE IIb

LEM MINIMUM ΔV BUDGET (FT/SEC)

ASCENT STAGE

(LIFT - OFF WT = 10,500 lbs.)

MISSION PHASE \ BUDGET ITEM	OPEN LOOP		GUIDANCE	FLIGHT MECHANICS CONTIN-GENCIES	EVAL. UNCER.	TOTAL
	ABSOLUTE MINIMUM	FLEX. ALLOW.				
LUNAR LAUNCH						
o To 50,000 ft.	5880	100*	120	100	60	6260***
o Ascent Transfer Orbital Insertion	100	10**	2		1	113
MIDCOURSE CORRECTIONS (RCS)			50			50
RENDEZVOUS (RCS)	97	89**	10		2	198
DOCKING (RCS)		25				25
					Total ΔV	6646

* 12 second vertical rise & finite pitch rate requirements

** $1/2^{\circ}$ plane change and non-Hohmann transfers

*** 213 ft/sec supplied by the RCS in the unbalanced couple mode of offset c.g. moment control and 17 ft/sec ullage.

MISSION PARAMETERS

1. CSM in 80 n. mi. altitude circular parking orbit.
2. $(T/W)_o$ at lift-off = 0.333

[redacted]

[redacted]

TABLE III

WORST NOMINAL MISSION RCS PROPELLANT LOADING

BASED ON THE ΔV BUDGET

Mission Phase	RCS Propellant Usage (Lbs)
Descent	
Prior to separation	
Checkout	4.1
Separation to end of insertion to Hohmann	
Separation and translation	15.7
Ullage settling	13.6
Attitude control & maneuvers	30.5
Coast and automatic powered descent	
Attitude control & maneuvers	55.6
Hover to Touchdown	
Manual landing	20.4
Prior to Lunar Launch	
Checkout	4.1
Descent Total	144.0
Ascent	
Lunar launch to end of insertion to Hohmann	
c.g. compensation	170.0
Attitude control & maneuvers	5.0
Coast, midcourse corrections, rendezvous and docking	
Translation	156.0
Attitude control & maneuvers	21.3
Ascent Total	352.3
Total for Ascent & Descent	496.3

NOTE: Total loading includes 22.7 lbs. for 9 hr. contingency orbit attitude control, plus 21.0 lbs. for single RCS tank failure at renderous, plus 9.6 lbs. for ullage during ascent, to give a total useable propellant of 549.6 lbs., plus residuals of 38.8 lbs., or a total loading of 588.4 lbs.

[redacted]

4.2.5 Worst Contingency Missions

As explained in section 4.2.2 of this report, there will be two RCS critical design missions. One will result when the requirements for total propellant are considered and a second will result when the requirements for single system propellant are considered. The results of the contingency analysis were applied to the abort cases shown in Figure 3.

4.2.5.1 Total RCS Propellant Sizing Critical Mission

The mission which sets the requirement for maximum total RCS propellant is one which is aborted 300 sec. after the start of powered descent. The particular worst case is the result of a failure which causes the loss of the ascent oxidizer supply. Aborts from points after 300 sec. have not been considered because the ascent engine would be necessary to complete the powered abort and this failure precludes use of the ascent engine. The abort can be accomplished by the descent engine alone from this point. This abort may concurrently be critical to the RCS thruster's burn time because it requires the greatest amount of propellant to be burned through the RCS thrusters.

If at 300 sec. after the start of powered descent the ascent oxidizer fluid is lost, then the c.g. of the LEM will be shifted outside of the 6° cone of the descent engine gimbal range. The resulting moment unbalance (see Fig. 5) must therefore be corrected for by the RCS thrusters during powered abort. The descent engine thrust during the abort must be limited such that the moment it creates is within the 2 jet control capability (1100 ft-lbs.) of the RCS. Use of 4 jet couple requires 32.9 lbs. less RCS propellant while allowing the maximum descent thrust to double. CSM rescue is still required with the 4 jet couple however, and hence the 2 jet case was considered critical. (2 jet couple operation is the normal G & N auto control mode). It is possible to abort with a thrust below this maximum allowable level; however, the propellant consumed by the RCS is a minimum when the abort is made with the maximum allowable thrust because the time required for the abort is shorter. It is assumed for this report that when the ascent stage oxidizer tank fails, the abort will be made with the maximum allowable descent engine thrust and hence the minimum RCS propellant required. This point may seem contradictory to the general philosophy of using the case which gives the greatest RCS propellant usage; however, an abort with minimum thrust is unrealistic.

[redacted]

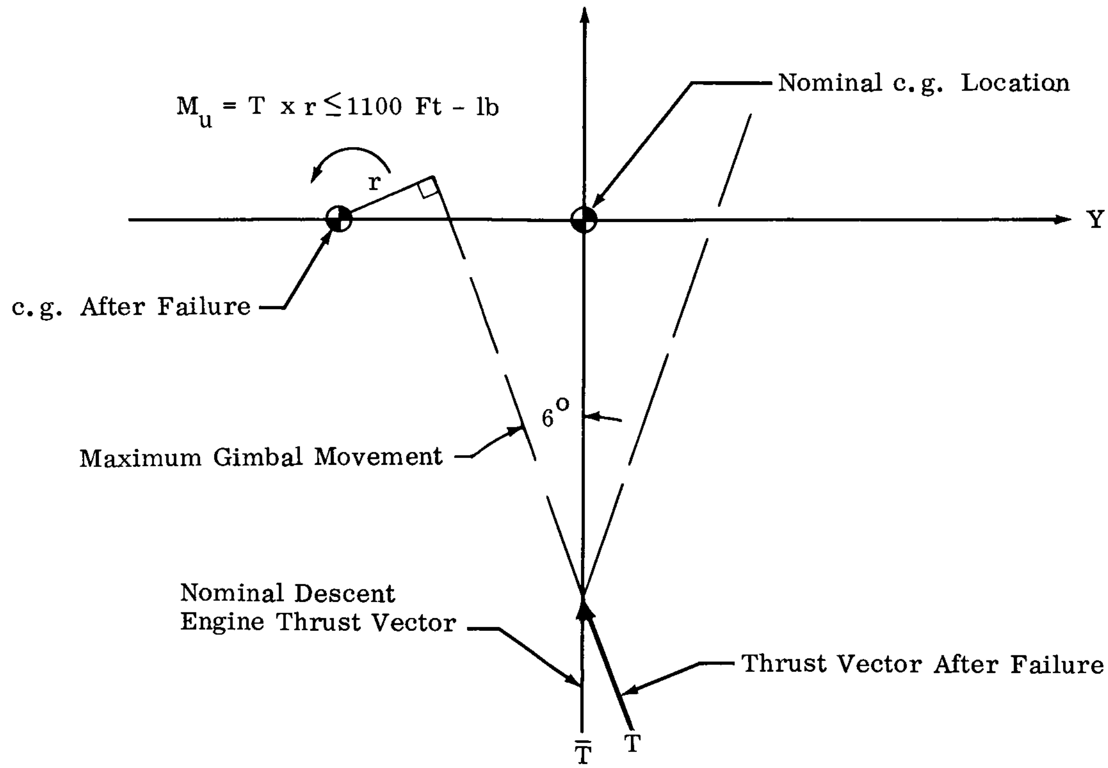

Figure 5 Moment Unbalance for Ascent Tank Loss During Powered Descent

This failure is most critical at 300 sec. after the start of powered descent (as opposed to aborts from earlier points) because the RCS propellant required is a maximum. The maximum allowable descent engine thrust is 4200 lbs. (Ref. 13) and all the descent propellant is consumed in completing the abort.

An outline of the RCS propellant used during this abort is presented here: (no rescue)

Worst nominal descent to abort point	73.00 lbs.
Correction for moment during powered abort	372.90 lbs.
Midcourse corrections (50 fps)	40.00 lbs.
Rendezvous (328 fps)	235.00 lbs.
Docking	12.65 lbs.
90 minute coast (5° limit cycle)	1.27 lbs.

[redacted]

[redacted]

0.3^{o} limit cycle during midcourse corrections and rendezvous (moments of inertia unknown)	1.87 lbs.
Correction for moment during rendezvous and midcourse correction due to offset c.g.	85.90 lbs.
Total RCS propellant used in completing abort	822.59 lbs.

Data on ΔV required for midcourse corrections and rendezvous for this particular abort are not available. Hence, it was assumed, for purposes of developing propellant consumption, that the "nominal" abort (full ascent stage) ΔV requirements for midcourse correction and rendezvous are good approximations for this abort (Ref. 10). It is therefore recommended that a further study of RCS propellant requirements be made for this abort.

It makes little difference whether the ΔV budget or the simulated data worst nominal mission is used to determine RCS propellant requirements up to the abort point. For this example the simulated data were used.

It is evident, from the above outline of RCS propellant required to complete the abort, that the present RCS tank size is inadequate for this contingency situation. However, if CSM rescue is provided, then a total of only 468.9 lbs. RCS propellant would be required to achieve a safe rescue position, and this is well within the present RCS design. In the CSM rescue case, the total burn time imposed by this contingency is 300 sec. which is within specification.

4.2.5.2 Single RCS System Propellant Sizing Critical Mission

In addition to the failure which sizes the total RCS propellant, the failure which sizes a single RCS system must also be considered. This failure is a manifold failure in the RCS which precludes the use of 1/2 of the RCS propellant and the use of the unbalanced couple mode of RCS operation. This failure is most critical on the lunar surface when the RCS tanks have been depleted by the maximum amount on the nominal mission, and the full c.g. moment control and ΔV contribution for the ascent are needed.

Several possibilities are considered and the data is summarized in Table IV. Propellant requirements are examined for the cases of CSM rescue and no rescue. Each of these cases is evaluated for two modes of propellant utilization -- i.e., ascent propellant supplying the RCS during the ascent, and RCS propellant supplying the RCS thrusters. The use of RCS propellant to feed the RCS thrusters results, for this failure, in asymmetrically

[redacted]

[redacted]

TABLE IV

Propellant Requirements for Abort From Lunar Surface Due to RCS Manifold Failure

NO CSM RESCUE

Basis For Propellant Requirements	Powered Ascent Mode	Ascent Propellant Required	RCS Propellant Required in Each System*	Total Propellant Required	Req'd Change In Sizing	Req'd Change In Loading
ΔV Budget	Ascent Propellant Supplies RCS and Ascent Engine	5068.7	249.3	5318.0	108.2	187.2
Simulation Requirements		4938.5	175.6	5114.1	0	0
ΔV Budget	RCS Propellant Supplies RCS Thrusters & Ascent Propellant Supplies Ascent Engine	4903.7	477.3	5381.0	171.2	250.2
Simulation Requirements		4856.5	320.6	5177.1	0	46.3
CSM RESCUE						
ΔV Budget	Ascent Propellant Supplies RCS and Ascent Engine	5002	95**	5097	0	0
Simulation Requirements		4874	83**	4957	0	0
ΔV Budget	RCS Propellant Supplies RCS Thrusters & Ascent Propellant Supplies Ascent Engine	4839	321**	5160	0	29.2
Simulation Requirements		4792	228**	5020	0	0

* This is for the full mission - descent and ascent

** 23 lbs. for contingency stay is included.

Total (Ascent & one RCS system) sized for: 5209.8 lbs.
loaded for: 5130.8 lbs.

Current Ascent Tank - sized for 4922 lbs.
- loaded for 4856 lbs.

Current RCS tank (each system) - sized for 575.2/2 = 287.8 lbs
loaded for 549.6/2 = 274.8 lbs

[redacted]

[redacted]

draining the RCS tanks and can increase the c. g. offset. This requires more propellant for moment control during the ascent.

Further, the propellant requirements are determined on the basis of simulation data and the Minimum ΔV Budget requirements. The ΔV Budget requirements are the most severe.

- No CSM Rescue

  If no CSM rescue is provided, and the powered ascent is performed by having the ascent propellant supply the ascent engine, and the RCS propellant supply the RCS thrusters, then the resulting propellant requirements, for powered ascent, are 4903. 7 lbs. for the ascent engine and 228 lbs. for the RCS thrusters. An additional 177. 3 lbs. is required by the RCS thrusters for rendezvous, midcourse correction and docking. The present ascent engine tank sizes are sufficient to handle this case. However, each RCS system must be increased in size such that 477. 3 lbs. of propellant can be loaded. That is, half of the RCS propellant required during descent (72 lbs.) and all of the required RCS propellant during ascent (405. 3 lbs.) must be supplied in each RCS propellant system. Because of this increase in ascent stage weight, the descent stage RCS and engine propellant requirements must necessarily increase.

  The RCS propellant requirements for this critical failure case can be lowered if the powered ascent is performed by feeding both the RCS thrusters and ascent engine with the ascent propellant. This procedure prevents asymmetrical draining of the RCS tanks and therefore does not aggravate the offset c. g. problem. For this case, 5068. 7 lbs. of ascent engine propellant is required. Hence, in order to complete the abort, the ascent propellant tanks must be increased in size from the present 4922 lbs. to 5068. 7 lbs. and increased in loading from 4856 lbs. to 5068. 7 lbs. The present RCS tank sizes are sufficient to complete the abort without CSM rescue if this increase is made. This increase in ascent stage weight would necessarily mean a further accompanying increase of approximately 800 lbs. in descent stage RCS and engine propellants.

- CSM Rescue of LEM

  If CSM rescue is considered, then only 6160 fps is required for the powered ascent; that is, the 113 fps associated with insertion is no longer required since only a safe parking orbit (50,000 ft. altitude) is required to complete the abort.

[redacted]

If the ascent is performed by feeding the RCS thrusters with RCS propellant and the ascent engine with ascent propellant, then the total RCS propellant required to attain a safe rescue orbit (50,000 ft.) is 321 lbs. and the ascent engine requires 4839 lbs. If ascent engine propellant is used to supplement the RCS propellant, then the present tank sizes are sufficient to attain the safe, 50,000 ft. parking orbit although the total propellant loading would have to be increased by 29.2 lbs. in order to meet the ΔV Budget requirements. Burn time is no greater than the normal ascent plus rendezvous.

If the ascent is performed by supplying both the RCS thrusters and the ascent engine with ascent propellant, then the propellant required, during powered ascent, in the ascent tankage is 5002 lbs. Although this is greater than the present ascent tank size, the RCS thrusters can be used to complete the powered ascent phase. If this is done, then an additional 7 lb. of RCS propellant is required for offset c.g. moment control during the RCS translation burn. Thus the loading would be

	Req'd	Present
Ascent	4856 lbs.	4856 lbs.
1 RCS tank	248 lbs.	274.8 lbs.

or a margin of 26.8 lbs.

The implications of this mode on other LEM systems must be investigated. The combination of RCS and ascent propellant is therefore sufficient to attain a safe rescue orbit (50,000 ft. altitude) with the present sizing and propellant loading.

The critical failure discussed above is one which results in the loss of both 1/2 the RCS propellant and the unbalanced couple mode of RCS operation. It is noted in the AMPTF contingency analysis (Ref. 12) that there are also several single failures that cause either the loss of 1/2 RCS propellant or loss of the unbalanced couple mode of RCS operation. CSM rescue is essential for crew safety in all these cases, as well as for the manifold failure case discussed above, with the present LEM propellant loading. These cases are not as critical as the manifold failure in terms of propellant required in the no rescue case, but the conclusion that rescue is required is further substantiated when these cases are considered.

[redacted]

4.2.5.3 RCS Thruster Burn Time in LEM Propulsion Backup Mode.

The maximum requirement on RCS thruster burn time occurs in the case where the LEM Propulsion is used for transearth injection with the CSM attached. The LEM RCS would be used (with ascent propellant) to provide transearth midcourse corrections. This mode of operation is described in Ref. 11. The burn time required with 4 X axis jets thrusting is a maximum of approximately 760 seconds. The design specifications on the thruster call for 500 sec. steady state operation and 500 sec. pulsed operation. It is the considered opinion of LEM RCS engineers that the 500 sec. pulsed operation is equivalent to more than 500 sec. steady state operation. It is therefore concluded that the maximum burn time requirements can be met with thrusters that meet the present design specification.

4.2.5.4 Summary of Worst Contingency Missions

The analysis of failures shows that the present RCS loading, propellant distribution, and burn time specification are satisfactory for all single failure cases if:

- CSM Rescue is provided
- The ascent propellant is cross fed to the RCS in an ascent with an RCS manifold failure
- The G & N can abort from powered descent with reduced thrust and
- The ascent to 50,000 ft. is completed using RCS thrusters.

If the ascent propellant is not increased, the present loading provides a margin of 26.8 lbs. in each RCS tank for the worst contingency under the above conditions.

4.2.6 Discussion of Results

4.2.6.1 Guidance and Evaluation Uncertainties

The determination of a realistic worst nominal mission is made difficult by the fact that the evaluation uncertainties and guidance errors during powered ascent have not been determined accurately. Secondly, the probability that any given guidance error or evaluation uncertainty will occur is not known. The conclusions drawn, as to the ability of the present propellant tank sizes to complete a mission, are greatly dependent upon the values of the guidance errors and evaluation uncertainties. For example, if the propellant requirements are as in the Minimum ΔV Budget (the errors and uncertainties total 183 fps) and an RCS manifold fails on the lunar surface, then the mission cannot be completed without CSM

[redacted]

rescue. That is, the propellant required in powered ascent through insertion is 5068.7 lbs. (This assumes the ascent tank feeds both RCS and main engines in powered ascent.) This is 146.7 lbs. more than the present ascent tank sizing (4922 lbs.) will permit. Therefore, the RCS would supplant the main engine at the end of the powered ascent phase. If this is done, the RCS propellant remaining (56.3 lbs.), is not sufficient to complete the ascent. Hence, some form of CSM rescue must be provided. If, on the other hand, guidance errors and evaluation uncertainties are assumed to be zero, then the present tank sizing has the capability of completing this abort without CSM rescue.

It is therefore evident that before a final evaluation of the present system can be made, the guidance errors and evaluation uncertainties must be determined accurately.

4.2.6.2 Rendezvous ΔV for Critical Design Mission

The rendezvous ΔV requirements have been determined for aborts from powered descent with a full ascent stage (all propellant on board); however, with less than the full ascent propellant load, the rendezvous ΔV requirements are not known. Hence, for the critical design mission, defined by an abort from powered descent as a result of an ascent oxidizer tank failure, the rendezvous ΔV requirements are not known. Nevertheless, propellant consumption during rendezvous was evaluated on the basis of the requirements for an abort with a full ascent stage. This is felt to be a good approximation.

Since this mission is critical to the RCS design, it is felt that a further study of this abort case should be made so that accurate results for RCS propellant requirements can be determined.

4.2.6.3 Simulation Data

In an attempt to get realistic RCS propellant requirements during the hover to landing phase, the GAEC Phase A simulation results were used. However, this simulation's results are for a two minute hover to landing phase and the worst case would be a three minute phase. In order to convert the available data to the worst case, additional maneuvers (two translations and two yaws) and their associated RCS propellant requirements were added to the simulation results.

Further, because of the unavailability of simulation data for X axis docking, the propellant requirements used in this report were based upon Z-axis docking simulations.

Both of these procedures are considered realistic and it is not anticipated that new simulation data will alter the conclusions of this report.

4.2.6.4 RCS Critical Design Mission

As noted in Section 4.2.4 of this report, there are two RCS critical design missions. The first critical mission - based on computed and simulation data RCS propellant requirements - determines the maximum propellant quantity burned by the RCS thrusters (822.59 lbs.) and the second critical mission - based on Minimum ΔV Budget - determines the maximum amount of propellant required (477.3 lbs.) in each RCS system. Both of these are based upon no CSM rescue.

The RCS critical design mission, which is defined by an abort from powered descent as a result of an ascent oxidizer tank loss, calls for 822.59 lbs. of RCS propellant if no CSM rescue is provided. If CSM rescue is provided, the present RCS design can provide propellant sufficient to achieve a safe rescue position. An alternate to supplying CSM rescue is to open up the maximum gimbal angle to 10°. This would allow the descent engine to correct for the moment unbalance without RCS usage and enable the present design to complete the abort without CSM rescue. Dumping the ascent fuel after staging decreases the RCS propellant required to complete the abort. Dumping alone however is not sufficient to eliminate the need for CSM rescue. It is feasible to combine opening up the gimbal movement and dumping the ascent fuel to allow the abort to be completed without CSM rescue and within the present RCS design.

The RCS critical design mission which results when the LEM Minimum ΔV Budget is used to dictate propellant requirements is outlined in Section 4.2.5. The worst case for this mission is when the RCS thrusters are supplied by RCS propellant and the main engine is supplied with ascent propellant during powered ascent. If no CSM rescue is provided, then the RCS propellant required to complete the abort is 954.6 lbs., or 405.0 lbs. more than the present loading schedule (549.6 lbs.) and 379.0 lbs. more than the present tank size (575.6 lbs.). However, if the ascent tankage is filled to capacity (present size), then it can supply (4922 - 4903.7) 18.3 lbs. to the RCS, thereby decreasing each RCS tank requirement by this amount. These requirements can be decreased by supplying both the RCS thrusters and the main engine with ascent propellant through powered ascent. For this case, provided the ascent tank size is increased to 5068.7 lbs., the present RCS tank sizes are sufficient to complete the abort without CSM rescue. This mode of ascent requires less propellant because in the former a c.g. shift and hence moment unbalance may be incurred by draining RCS propellant from only one system. Now, if CSM rescue is provided, then either method allows ascent to a safe rescue altitude. However, the mode which requires the least propellant is recommended, i.e., feed all engines with ascent propellant throughout powered ascent for the contingency case discussed.

It is not recommended to increase the ascent propellant to provide for supplying the RCS thrusters for the nominal ascent. If this were done, and the RCS off-loaded correspondingly, the total RCS propellant would not be sufficient to handle the worst case of abort from powered descent due to ascent oxidizer loss even with CSM Rescue.

4.2.7 Summary of Results

The analysis discussed here and in the Contingency Analysis have shown the critical failures can be listed as follows in order of RCS propellant margins for the mode of operation required.

1. Ascent tank loss 300 seconds into powered descent - no rescue. Total margin = -272.9 lb.
2. Manifold loss on lunar surface - no rescue. Single RCS margin = -187.2
3. 1 RCS tank loss at rendezvous - no rescue. Single RCS margin = 0
4. Manifold loss on lunar surface - rescue. Single RCS margin = +28.6
5. Ascent tank loss during powered descent - rescue. Total RCS margin = +80.7
6. 1 RCS tank loss at rendezvous - rescue. Single RCS margin = +143.3

The ranking shown here is based upon ΔV Budget requirements and the margin quoted is with respect to current loading. The ranking of condition 4 depends upon crossfeed of ascent propellant to the RCS during the main ascent burn and completing the burn to 50,000 ft. the RCS. The present tank loading is based upon condition 3. This is a case of no rescue and represents an increase of 21 lbs. over the ΔV requirements for the nominal mission, as shown in Table III. It might be argued that the RCS should not be loaded for any no rescue case other than the nominal. In which case this 21 lbs. could be off-loaded and the worst contingency would have a single tank margin of 16.3 lbs. This would be a small margin for a failure that is not remote.

Therefore, it is not recommended to reduce the present tank loading.

[redacted]

5. CONCLUSIONS AND RECOMMENDATIONS

It is concluded that the present RCS system design is adequate in terms of propellant sizing, propellant loading, tankage distribution and burn time to meet all nominal and single-failure mission requirements if CSM Rescue is provided.

However this conclusion requires that an ascent be made (in the case of RCS manifold failure on the lunar surface) with ascent propellant supplying the RCS jets. If this is not done, either ascent propellant loading or RCS tank sizing must be increased to cover all cases according to the ΔV Budget requirements. An ascent made in this manner may require the final portion of the ascent burn to be completed on the low thrust RCS system. (maximum of 230/fps required). The implications of this mode must be studied.

The ascent stage presently counts upon a ΔV contribution from the RCS in order to meet the ascent ΔV Budget in the no-failure or nominal mission. It is recommended that provisions be made in the SCS logic to guarantee that this contribution can be realized for the full range of possible nominal c. g. offsets. This is recommended so that c. g. location is not critical to mission completion. The use of RCS to complete the ascent burn could satisfy this requirement.

It is recommended that further studies be made to define more accurately the RCS propellant required for aborts from powered descent, and to define the guidance and evaluation uncertainties associated with the powered ascent.

It is also recommended that G&N studies of aborts from powered descent with reduced thrust (below the RCS saturation level with the large offset c. g. resulting from loss of ascent oxidizer) be made.

Finally in view of the above, it is recommended not to change RCS tank sizing or loading at this time.

[redacted]

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